Corrosive wear in crosshead diesel engines

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Existing theories describe corrosive wear in crosshead diesel engines in terms of acid condensation, when the temperature in the combustion space drops below the dew point. Here a theory is proposed which stresses the role of alkaline cylinder lubricants in protecting the metal surface. Calculated liner wear rates as a function of fuel sulphur content, feed rate and alkalinity of the oil, and axial position are in satisfactory agreement with experimental data.

Keywords: *corrosive wear, cylinder oil, crosshead engine*

Introduction

Economic operation is currently a key issue in the world of marine propulsion. Engine manufacturers are building their engines with strong emphasis on fuel efficiency and reliability. Ship owners economize on operational staff and demand low maintenance costs. Cost-effective lubrication is one of the elements that contribute to controlling costs. It involves an appropriate balance of lubricant costs and engine component lifetime. High cylinder liner wear is counteracted by increasing the oil feed rate for example. Corrosion quite frequently dominates the liner wear of crosshead diesel engines, particularly when the engines are running on heavy residual fuels. The severity of this process is typically controlled by an appropriate supply of alkaline lubricants. A higher total base number (TBN) or an increased feed rate reduces wear and vice versa.

As early as the forties Broeze and Wilson[1] described the mechanism of corrosive wear. According to this mechanism sulphur trioxide is formed in the combustion gas, forms sulphuric acid with water vapour, condenses and finally attacks the liner and piston rings. Dew point temperatures and the formation of condensates have been investigated by Muller[2], Golothan[3] and more recently by Teetz[4]. Their approach focuses on condensation of sulphuric acid onto the metal surface, which process depends among other factors, on the pressure of the combustion gas and the temperature of the liner surface. Condensation occurs if the temperature drops below the dew point of sulphuric acid, the amount of condensate being related to the partial pressure of the acid.

This semi-quantitative approach has proved to be quite useful. It predicts, for instance, the effect of liner temperature on corrosive wear rather well; however, there are two problems. First, the presence of oil at the metal surface is neglected. This is a severe limitation, because the amount and composition of the lubricant has a significant influence on corrosive wear. Secondly, theory predicts that no corrosion occurs if the liner temperature is above the dew point of sulphuric acid. This is in contrast with our experience with a Sulzer 2RNF68M engine, where lubricant TBN and fuel sulphur content continue to be very important well above 130°C liner temperature[5].

Recently, we have reported on a totally different approach to describe corrosive wear[6]. Its principal feature is to highlight the role of the lubricant. The oil acts as a barrier to acid species and protects the metal surface even though some acid is transported from the combustion gas to the surface.

In this paper we will detail the calculation procedure of our corrosive wear model, indicate its main benefits and deficiencies and present some new results, particularly relating to the effects of oil film thickness and axial position on liner wear.

The model

Work in our laboratory engines has shown that corrosion is governed by the amount of base present at the liner surface. In other words, it is the alkalinity throughput and not the oil feed rate that matters. We have also found that alkalinity depletion does not depend on the TBN of the fresh oil. Nor does TBN depletion as such correlate with engine wear. Apparently, it is not important how much base is neutralized and it is rather the quantity of unreacted acid that determines the extent of corrosion.

The evidence suggests that corrosive wear results from four successive steps: (i) formation of acid species in the combustion gas, (ii) transfer of acid to the oil film, (iii) partial neutralization of acid in the oil by alkaline additives and (iv) adsorption of unreacted acid at the metal surface with subsequent corrosion.

To simplify this complex process we assume that the oil can be treated as a homogeneous medium, ie the temper-

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Notation

A	surface area of liner ring, m^2
$C_{A/B}$	concentration acid (base) in lubricant or in combustion space (indicated by superscript G), molecules m^{-3}
D	cylinder bore, m
k_1	residual oil volume, m^3
k_2	oil combustion rate constant, $m^3\ s^{-1}$
k_3	wear rate conversion constant 8.5×10^{-16} mm rev. molecules $^{-1}$ 1000 h^{-1}
k_N	neutralization rate constant 1.4×10^{-6}, m^3 molecules $^{-1}$ s^{-1}
$k_{W/G}$	mass transport coefficient across oil/metal and oil/gas interface 1×10^{-2}, m s^{-1}
l	length of connecting rod, m
$N_{A/B}$	number of acid (base) molecules in oil film, molecules
r	piston stroke divided by two, m
t	time, s
t_e	time interval of one piston stroke, s
V	oil volume at liner surface, m^3
V^G	combustion space volume, m^3
V_{TDC}	combustion space volume with piston at top dead centre, m^3
w	wear rate, mm 1000 h^{-1}
x	position of lowest piston ring, m
λ	ratio of r/l
ω	angular velocity of crankshaft, rad s^{-1}

ature gradient across the oil film due to heat flow is neglected. Also at a given position on the liner or piston ring no spatial concentration gradients are assumed however, concentrations may vary in time.

Another important assumption relates to step (iv). Corrosive wear rates are calculated from the amount of acid wetting the surface. This means that corroded material is being removed from the surface and fresh metal is made available for further chemical attack. Finally, the influence of viscous oil drain during one piston stroke is considered to be negligible.

With these assumptions we can write material balances for base and acid species in the lubricant film. The rate of base depletion at a certain position on eg the cylinder liner is

$$\frac{dN_B}{dt} = C_B \frac{dV}{dt} - k_N V C_A C_B;\ N_B(t_0) = N_{B,0} \qquad (1)$$

where N (or C) denotes the number (or concentration) of molecules in oil volume V. Subscript B refers to base, subscript A to acid. The right-hand side of Eq (1) contains two terms, one for the combustion of oil while it is exposed to the combustion gas and the other for the neutralization of acid by lubricant TBN and k_N is the rate constant of the neutralization reaction. (All symbols are explained in the notation).
Similarly the acid material balance is

$$\frac{dN_A}{dt} = C_A \frac{dV}{dt} - k_N V C_A C_B + k_G A(C_A^G - C_A) - k_w A C_A;\ N_A(t_0) = N_{A,0} \qquad (2)$$

which indicates that in addition to oil combustion and neutralization, there are the effects of mass transfer from the gas phase and of wetting of the metal surface. Superscript G means concentration in the gas phase. k_G and k_w are mass transport coefficients.

This set of coupled differential equations can be written as

$$\frac{dy}{dt} = f(t, y) \qquad (3)$$

with

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} N_B \\ N_A \end{bmatrix} \qquad (4)$$

and

$$f = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} \frac{dV}{dt}\frac{y_1}{V} - k_N \frac{y_1 y_2}{V} \\ \frac{dV}{dt}\frac{y_2}{V} - k_N \frac{y_1 y_2}{V} - A\frac{y_2}{V}(k_w + k_G) + k_G A C_A^G \end{bmatrix} \qquad (5)$$

Eqs (3-5) are numerically integrated according to the implicit difference equation

$$y_{n+1}^{i+1} = y_n + h_n[(1-\alpha)f(t_n, y_n) + \alpha f(t_{n+1}, y_{n+1}^{i+1})] \qquad (6)$$

where h_n is a variable step size and α is a fixed parameter. n is the number of the time step and i is the iteration number required to eliminate y_{n+1}^{i+1} from the right-hand side of Eq (6). For sufficiently small $y_{n+1}^{i+1} - y_{n+1}^{i}$ the iteration is achieved with

$$f(t_{n+1}, y_{n+1}^{i+1}) - f(t_{n+1}, y_{n+1}^{i}) \cong \bar{J}_{n+1}(y_{n+1}^{i+1} - y_{n+1}^{i}) \qquad (7)$$

with the Jacobian

$$\bar{J}_{n+1} = \begin{vmatrix} \frac{\frac{dV}{dt} - k_N y_2}{V} & -k_N \frac{y_1}{V} \\ -k_N \frac{y_2}{V} & \frac{\frac{dV}{dt} - k_N y_1 + A(k_w + k_G)}{V} \end{vmatrix} \qquad (8)$$

Substitution of (7) into (6) and rearrangement lead to

$$y_{n+1}^{i+1} = y_{n+1}^{i} - (\bar{W}_{n+1})^{-1} \times [y_{n+1}^{i} - y_n - (1-\alpha)h_n f(t_n, y_n) - \alpha h_n f(t_{n+1}, y_{n+1}^{i})] \qquad (9)$$

with

$$\bar{W}_{n+1} = (\bar{I} - \alpha h_n \bar{J}_{n+1}) \qquad (10)$$

and $\bar{I}$ the identity matrix. Eq (9) describes the solution method of the numerical integration procedure, which is started with

$$y_{n+1}^{0} = y_n + h_n f(t_n, y_n) \qquad (11)$$

For α a value of 0.55 has been taken, giving an integration method that results in a numerical solution accurate to at least two significant figures.

The integration result is a base and acid concentration in the oil film as a function of time. The time interval taken is the time required for one piston stroke.

These concentrations are very difficult if not impossible to measure *in situ*, but the acidity of the oil film can be related to corrosive wear according to

$$w = k_3 k_w A \int_0^{t_e} C_A(t)\,dt \quad (\text{mm } 1000\ \text{h}^{-1}) \qquad (12)$$

where k_3 converts the mass transport of acid to the metal surface per piston stroke into a wear rate in mm $1000\ \text{h}^{-1}$.

The actual calculation requires numerical data of acid in the combustion gas, the amount of oil present at the liner surface, the magnitude of the oil/gas and metal/oil interfacial areas, the magnitude of the kinetic parameters k_w, k_G and k_N, and finally the boundary condition for acid and base concentration in the oil.

Acid concentration in combustion gas

We will use a simple approach to estimate the amount of sulphur trioxide in the combustion gas. The number of sulphur trioxide molecules formed in the combustion gas during each stroke is calculated from the sulphur content of the fuel, assuming complete conversion into sulphur dioxide.

Cullis *et al*[7] estimate that a few mole percent oxidizes further to trioxide. We have taken a value of 5%. Also it is assumed that all the corrosive species are formed instantaneously upon injection and that during the upward movement of the piston no further change in acid concentration occurs. Obviously, this is only a crude approximation to reality, but the analysis below demonstrates that it produces quite satisfactory results.

The acid concentration decreases with the downward movement of the piston,

$$C_A^G(t) = \frac{N_A^G}{V_G(t)} \qquad (13)$$

with $V_G(t)$ the volume of the combustion space given by

$$V_G(t) = V_{TDC} + \pi D^2\,(2r - x(t)) \qquad (14)$$

where the position of the piston $x(t)$ is

$$x(t) = r(1 + \cos \omega t) - l[1 - (1 - \lambda^2 \sin^2 \omega t)^{1/2}] \qquad (15)$$

Eqs (13-15) determine the acid concentration in the gas. This concentration decreases strongly with time but when the piston has reached the bottom dead centre it does not change any further during the remainder of the stroke.

Oil film thickness

In Ref (6) no attempt was made to describe the effect of oil film thickness on the calculated results. In the slightly modified model reported here this parameter is included. At a certain position of the liner one has

$$V(t) = k_1 + k_2(t_e - t),\ 0 \leqslant t \leqslant t_e \qquad (16)$$

where k_1 corresponds with the residual oil volume after combustion at the end of the stroke, and $k_2(t_e - t)$ represents the amount of oil which is combusted during the stroke and replenished during the next one. Eq (16) assumes a constant oil combustion rate, yielding a linear decrease of oil volume (film thickness) with time.

Magnitude of mass transport

Transfer of acid into the oil phase and from the oil onto the metal surface depends on the interfacial area and on the values of the coefficients k_G and k_w. The magnitude of the metal surface area is probably of the order of the geometrical area. (If wear occurs only surface asperities are being removed). The size of the oil/gas interface will depend on the oil film thickness. For extremely thin films it will be close to the microscopic surface area, whereas for thicker lubricant films it will be closer to the smaller geometrical area.

The kinetic constants k_G and k_w are of the order of 10^{-4} to 10^{-2} m s^{-1}. Calculations have been performed with $k_w = k_G = 10^{-2}$ m s^{-1}, and with A_{metal} equal to the geometrical surface area and A_{gas} equal to seven times the geometrical area (discounted in K_g).

Earlier work in our laboratory had indicated that k_w is of the order of 1.4×10^{-6} m^3 $molecule^{-1}$ s^{-1}.

Initial conditions

Again we have chosen a slightly modified approach compared with Ref (6). Rather than assuming the acid concentration in the oil to be zero at the start of the calculation, we can calculate from Eq (2) with the condition that C_A does not change with time after base depletion, that

$$C_{A,e} = \frac{k_G C_A^G(t_e)}{\left(-\frac{1}{A}\frac{dV}{dt} + (k_G + k_w)\right)};\quad N_{A,0} = C_{A,e} V(0) \qquad (17)$$

The base concentration follows immediately from the amount of oil supplied to the position which is considered, ie if the base was fully depleted during the previous cycle.

Table 1 Sulzer 2RNF68M characteristics

Stroke	1.25 m
Position of lubrication quill	1.154 m
Cylinder bore	0.68 m
Length of connecting rod	2.375 m
Combustion space volume V_{TDC}	4.12×10^{-3} m^3
Power output/cylinder	1.17×10^3 kW/cylinder
Crankshaft velocity	1.30×10^2 r/min
Specific fuel consumption	2.30×10^2 g kWh^{-1}
Lubricant feed rate	0.85 g kWh^{-1}
Lubricant alkalinity	70 mg KOH g^{-1}
Fuel sulphur content	$2\text{–}5 \times 10^{-2}$ g g^{-1}
Residual oil film thickness	10^{-9}–10^{-4} m

Results

Calculations have been done with our Sulzer 2RNF68M engine[5] serving as an example. The engine data needed are summarized in Table 1. The effect of fuel sulphur content has been recalculated with the modified model, yielding almost identical results to Ref 6. Fig 1 shows that base concentration in the oil film decreases and that the base may eventually be fully depleted due to the neutralization reaction. This trend becomes more severe if the fuel contains more sulphur.

When base is depleted the acid concentration builds up and this leads to corrosion. Wear rates are shown in Fig 2. Theory predicts a strong increase with increasing sulphur levels. The trend is the same as observed in practice[8].

The effects of lubricant TBN and feed rate have already been reported in Ref (6). We have also calculated wear rates at different positions on the liner. The base depletion time is enhanced further away from top dead centre (TDC) (Fig 3), and the wear rate reduces (Fig 4), because of two simultaneous effects. Firstly, the exposure time of

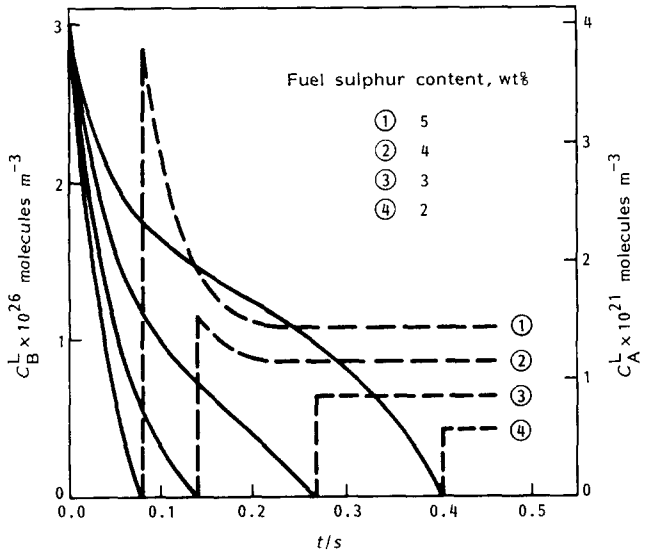

Fig 1 Calculated cylinder oil additive depletion at liner TDC area of sulzer 2RNF68M engine. Solid curves refer to base concentration, broken curves to acid concentration

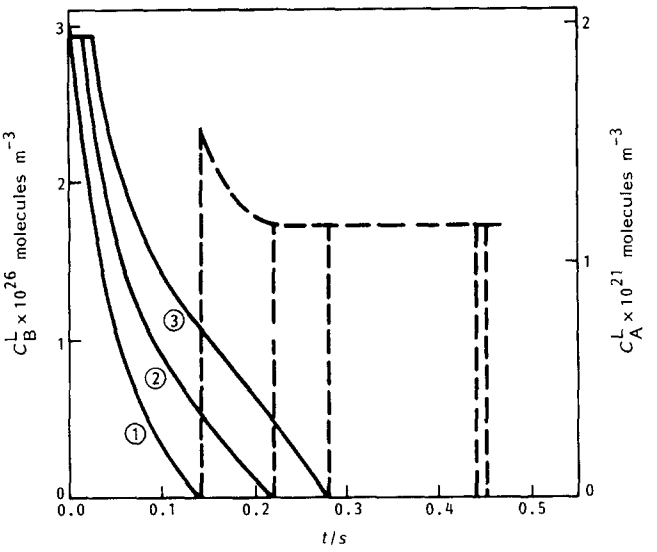

Fig 3 Calculated cylinder oil additive depletion in sulzer 2RNF68M engine. Effect of position at liner surface 1 TDC; 2 1 cm below TDC; 3 4 cm below TDC solid curves refer to base concentration, broken curves to acid concentration

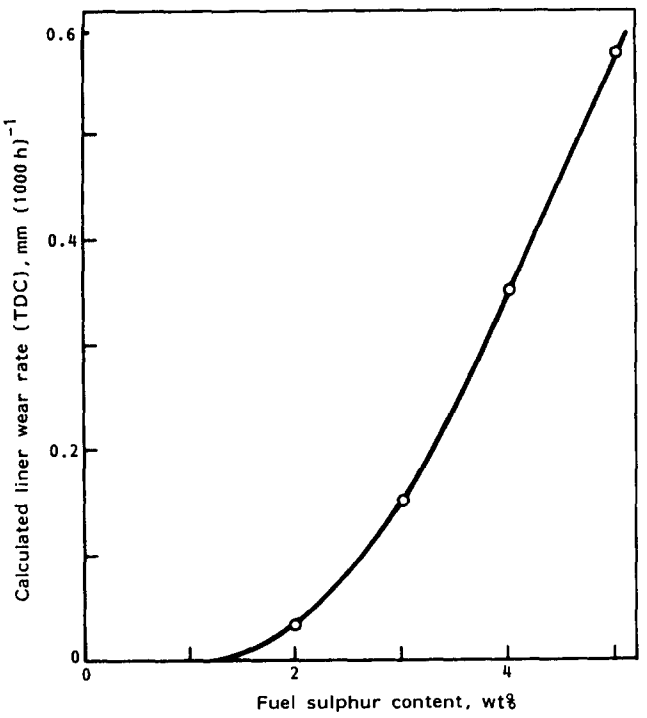

Fig 2 Calculated cylinder liner (TDC) wear in sulzer 2RNF68M engine. Effect of fuel sulphur content. Alkalinity throughput 60 mg KOH (kWh)$^{-1}$

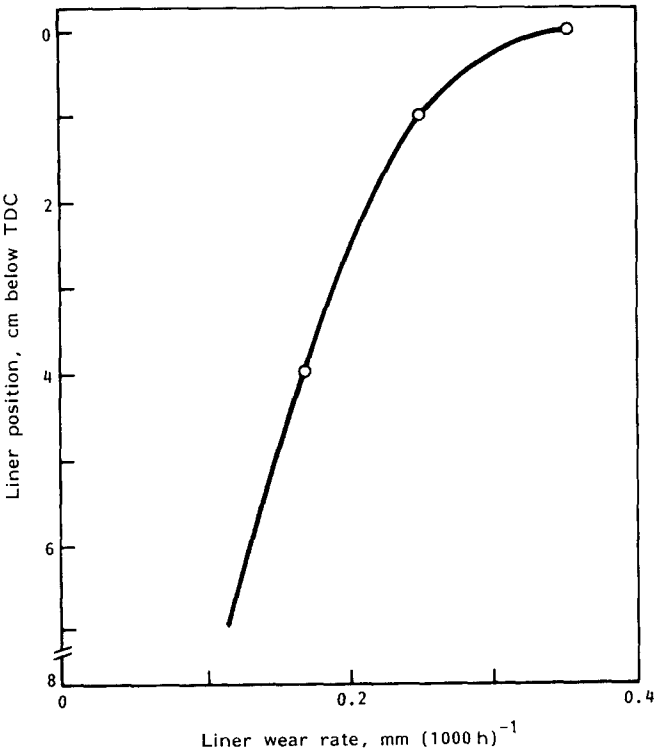

Fig 4 Calculated cylinder liner wear in sulzer 2RNF68M engine. Fuel sulphur content 4.0 wt %. Alkalinity throughput 60 mg KOH g^{-1}

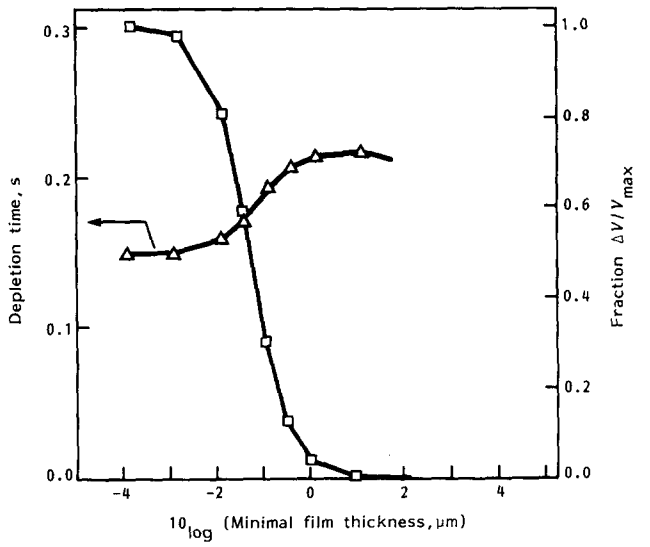

Fig 5 Effect of residual oil film thickness on cylinder oil additive depletion time. TDC position, fuel sulphur content 3 wt%; alkalinity throughput 11 mg KOH(kWh)$^{-1}$

the oil to the combustion gas increases at positions lower than TDC, and secondly, the concentration of sulphur trioxide is reduced due to volume expansion.

The results in Fig 4 are in satisfactory agreement with experimental data, which invariably show higher wear depth at TDC and lower values at lower positions. The trend suggests that wear rate increases even more beyond TDC. This will not occur, however, because the model assumes continuous removal of corroded iron by mechanical action of the piston rings. Clearly such rubbing will not occur above TDC. As a result a protective layer of iron sulphate is formed which inhibits further corrosion, and the overall wear rate will be low above TDC.

The above calculations have been performed assuming a residual lubricant film thickness of 0.01 μm *ie* at the end of the stroke after combustion of the oil a very thin film is assumed to remain present on the liner surface. The effect of this residual film thickness on base depletion time is shown in Fig 5. With very thin residual films, when the amount of fresh oil that is supplied with each stroke is large compared to the remaining oil, the base depletion time does not depend on film thickness and the same applies for relatively thick films much larger than the amount of fresh oil. In between there is a transition region, when the depletion time increases with residual oil film thickness. The notion of enhanced TBN depletion time with thicker oil films is interesting. It provides an alternative explanation to the effect of oil viscosity on liner wear. Normally this is explained as a hydrodynamic protection against adhesive wear. Our results show that reduced corrosive wear can equally well explain the benefit of high viscosity oils.

Discussion

The above results and those in Ref (6) have illustrated that our corrosive wear theory yields a crude but essentially correct description of the processes occurring in crosshead diesel engines. The most striking feature is its neglect of acid condensation/dew point considerations and its emphasis on the role of the lubricant. As such it is a complementary approach to existing condensation theories. A next generation theory should incorporate the two different approaches into one more general theory of corrosive wear in crosshead diesel engines.

Returning for the moment to the role of the lubricant, we can state that our model is as yet flexible because certain parameters which are not (well) known have been used as fitting parameters. In the future many of these parameters, such as the kinetic constants for mass transfer and the concentration of sulphur trioxide in the combustion gas, can be measured experimentally. This will produce a much more rigid description, which would quantify the qualitative understanding generated here.

Conclusions

Corrosive wear in crosshead diesel engines can be described as a combined effect of (i) uptake of sulphur trioxide from the combustion gas into the lubricant film, (ii) neutralization of this acid by alkaline detergent additive in the oil, (iii) wetting and subsequent corrosion of the metal surface by unreacted acid, while part of the oil film is combusted when it is exposed to the flame front.

A striking feature of the model is its neglect of acid condensation/dew point considerations and its emphasis on the role of the lubricant. Calculated wear rates as a function of fuel sulphur content, feed rate and alkalinity of the oil are in qualitative agreement with experimental data. The model also explains why liner wear is at a maximum at top dead centre and less at lower positions.

The effect of residual oil film thickness has also been quantified.

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